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Modeling Minneapolis Skyway Network

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Abstract

Adopting an agent-based approach, this paper explores the topological evolution of the Minneapolis Skyway System from a microscopic perspective. Under a decentralized decision-making mechanism, skyway segments are built by self-interested building owners. We measure the accessibility for the blocks from 1962 to 2002 using the size of office space in each block as an indicator of business opportunities. By building skyway segments, building owners desire to increase their buildings' value of accessibility, and thus potential business revenue. The skyway network in equilibrium generated from the agent model displays similarity to the actual skyway system. The network topology is evaluated by multiple centrality measures (e.g., degree centrality, closeness centrality, and betweenness centrality) and a measure of road contiguity, *roadness*. Sensitivity tests such parameters as distance decay parameter and construction cost per unit length of segments are performed. Our results disclose that the accessibility-based agent model can provide unique insights for the dynamics of the skyway network growth.

Keywords: skyway network, network growth, agent-based modeling

1 Introduction

The skyway system, consisting of glass-enclosed bridges that connect enclosed buildings, is a peculiar artifact of human activities. Such an infrastructure enables pedestrians to move more efficiently between the connected buildings without being exposed to severe weather conditions and traffic (Corbett et al., 2009). While functioning similarly to ordinary roads in terms of connect destinations, the skyway system is different from other transportation

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networks in the following aspects. First, it is above the street level and only connect adjacent buildings (often in the central business district area). Second, it only allows pedestrian traffic. Third, although constructed under the cooperation between public agency and private business owners, the skyway links are frequently privately financed and owned. So why build skyways? While it is often believed that it is mainly because of the need to protect pedestrians from inclement weather, Byers (1988) argues that other more important reasons include: (1) relieving downtown congestion. (2) enhancing the profitability of downtown businesses by providing better visibility for the second floor of office buildings.

Just as Rome was not built in a day, the development of the skyway system is also incremental. It is therefore of interest to model the evolution of skyway networks over time. From a systems perspective, although hierarchical order of road networks is often designed by governments (for instance, since its inception in 1921, federal financial aid has funded improvements of the most important roads in the US (Rae, 1971)), order can also emerge from decentralized and spontaneous interactions of individuals (Ben-Joseph, 2005); the birth of Minneapolis Skyway System is an example par excellence. It begins with a private effort to provide better access to the NorthStar Center which is the city's first mixed-use complex. Further, sponored by private business owners, it grows mostly sustainably from 1976 to 1985 with the hope of expanding profitability of the office buildings in downtown by enriching the pedestrian experience.

In this research, we model the topological changes of the skyway network. We employ the agent-based approach to investigate the phase changes of skyway networks. Featuring the bottom-up approach, this approach fits the context of skyway networks in two terms. First, business owners of the downtown office buildings desire to enhance the volume of foot traffic to keep more customers in buildings by providing better accessibility to each other. Second, the economic benefit for the downtown properties will only become prominent when the network effect comes into play.

Instead of modeling an artificial scenario, we specifically examine the growth of the Minneapolis Skyway System in downtown Minneapolis. Started in 1962, the Minneapolis Skyway System has the longest network length and is mostly well-known in the US (Byers, 1988). Moreover, we have the geo-code network and the space size of each block from 1962 to 2002, providing a data foundation for modeling. Considering that the skway segments are built by individual business owners, our model examine the network growth from scratch. The generated network in equilibrium is further measured and compared with the actual network.

The rest of the paper is organized as followed. Section 2 reviews literature on modeling road network growth. The basic facts and statistics about the Minneapolis Skyway System are summarized in Section 3. Section 4 further introduces our agent model. Section 5 compares the simulated skyway network with the actual network. The last section discusses the implication of our results and concludes the paper.

2 Literature review

Transportation networks, displaying interesting pattern and order, have been a topic of interest for decade. Examples include as airline networks (Guimera et al., 2005; Guimera and Amaral, 2004), railways (Seaton and Hackett, 2004; Sen et al., 2003), subways (Latora and Marchiori, 2002), highway networks (Schadschneider et al., 2005), roads (Levinson and Yerra, 2006), and skyway systems (Corbett et al., 2009). A spectrum of models has been proposed to shed light on the mechanism of network growth. Graphically, for surface transportation networks, intersections can be seen as nodes and road (skyway) segments as links (or the other way around as in the "dual" case). Based on this structure, the models to examine road network growth can be cataloged into three streams distinguished by modeling perspective.

First, in *graphic-theoretic models*, each link is presumably born with a probability. An overview of graphic-theoretic view of spatial systems can be found in Haggett and Chorley (1969). The advantage of this approach is that it can build road network from scratch and dig into the process. A model is judged by how similar the output it produces is similar to the observant patterns. A notable example is the random graph model, arguably the first application of modern graph theory to explain real-world networks (Erdös and Rényi, 1959). Other approaches include the exponential model (Dorogovtsev and Mendes, 2002), preferential attachment model(Price, 1965; Barabási and Albert, 1999), Markov graph (Frank and Strauss, 1986; Wasserman and Pattison, 1996), and Newman-Gastern model (Gastner and Newman, 2006).

The second category is *network design models*, where given a set of specifications networks are constructed to optimize a centralized objective, such as minimizing the Euclidean distance(Gastner and Newman, 2006), minimizing detour (Schweitzer et al., 1998), or maximize transportation potential bewteen two locations (Yamins et al., 2003), and minimizing total transportation costs (Los and Lardinois, n.d.; Steenbrink, 1974). Minoux (1989) and Yang (1998) overviews the models and analytical methods in network synthesis and optimum network design problems; Guihaire and Hao (2008) reviews the models and algorithms in planning urban transit networks.

Third, in *agent-based discrete choice models*, decision-making agents construct links with local objectives. This approach, born in the Complex Network Theory (Boccaletti et al., 2006), has become increasingly popular due to its strength in digging to the fine granularity of the dynamics of a system. For example, Helbing et al. (1997, 1998) adopts an active walker model to model the evolution of trails in urban green spaces. Yerra and Levinson (2005) models network growth with localized investment rules. Treating links as autonomous agents, Levinson and Yerra (2006) investigates the self-organization of road networks using a travel demand model coupled with revenue, cost, and investment models. Xie and Levinson (2009) adopts the approach of iterative processes of network loading, traffic demand dynamics, investment, and disinvestment. Schadschneider et al. (2005) proposes a cellular automata model to predict the traffic jam probability for key nodes. Such decentralized agent-based approaches provide a bottom-to-top perspective to examine phase changes of network growth, path dependency (Arthur, 1989) and multiple equilibria (Yang, 1998; Corbett et al., 2009).

The model that is mostly related to our model in investigating skyway network growth is by Corbett et al. (2009), where in each iteration the link that can provide the highest increment of accessibility for the two blocks it connects is built. Accessibility is found as an important index for predicting skyway network growth Corbett et al. (2009). It is, however, limited in the following aspects: first, requiring only one link can be built is a too strong assumption in that multiple links are built in certain years in reality (for example, 13 segments were built in year 1992). Second, it cannot shed light on the interactions of different business owners who financed different links in the network. This paper aims to provide insights into micro-economic mechanism of the skyway system.

3 Measures of the topological attributes

Similar to Crucitti et al. (2006), some centrality measures are used to evaluate the networks: degree centrality (D), closeness centrality (C), betweenness centrality (B). While these concepts are originally proposed to measure certain properties for each node, here we calculate their mean values for all nodes/roads to assess the collective structural feature. In addition, we propose a measure of roadness (R) to evaluate the connectivity of links.

3.1 Centrality measures

Let's assume undirected graph G of J nodes (potential junctions) and K links; the graph can be represented by $J \times J$ matrix, where an element equals 1 if the link exists, 0 otherwise. This is a sparse matrix because links can only be constructed parallel to the x axis or y axis. Degree centrality is based on the idea that important nodes have the largest number of ties to other nodes in the graph. Based on Wasserman and Faust (1994), the degree centrality of node i is defined as:

$$D_i = \frac{\sum_{j=1}^{J} a_{ij}}{J-1} = \frac{p_i}{J-1} \tag{1}$$

where p_i is the degree of node i, i.e., the number of nodes adjacent to i.

Closeness centrality, C, is used to measure to which extent a node i is near to all the other nodes along the shortest paths (Sabidussi, 1966). The closeness centrality of node i is calculated as:

$$C_i = \frac{J-1}{\sum_{j \in G, j \neq i} d_{ij}} \tag{2}$$

where d_{ij} is the shortest path length between node i and node j, the smallest sum of the edges length throughout all the possible paths in the graph between i and j.

Betweenness, a measure of centrality of a node in a network, is the fraction of shortest paths between node pairs that pass through the node of interest. Nodes that occur on more shortest paths between other nodes have higher betweenness centrality. The betweenness centrality of node i equals:

$$B_i = \frac{1}{(J-1)(J-2)} \sum_{j,h \in G, j \neq h \neq i} n_{jh}(i)/n_{jh} \tag{3}$$

where n_{jh} is the number of shortest paths between j and h, and $n_{jh}(i)$ represents the number of shortest paths between j and h which contain node i.

In this research, the multiple centrality measures are calculated through the UCINET 6 Social Network Analysis Software (Borgatti et al., 2002).

3.2 Roadness measure

Further, we propose a new concept, *roadness*, which is designed to measure the continuity of emerged roads and how different the road patterns are from a fully-connected grid-like network. A road is defined as a series of sequential links, where the angle of two contiguous links equals 180 degrees [1]. The roadness of a network, R, is defined as the sum of the length of all roads over the total number of roads. In this research, since all the road segments have the same length, so we use the number of total segments to represent the sum of the length all segments (i.e. all links can be seen as having unit length). Mathematically, roadness is represented as:

$$R = \frac{\sum_{u=1}^{U} \gamma_u}{U} \tag{4}$$

Where U indicates the total number of roads, and γ_u the number of links on road u. Some examples to caculate roadness are shown in Fig. 1. The algorithm to identify the roads is shown in the appendix.

4 Minneapolis skyway system

The Minneapolis skyway system is the most famous grade-separated system in the US (source). The city's first skyway connects the NorthStar Center and the Northwestern Na-

[1] Here we use a grid, so road segments intersect at either 90 or 180 degrees. More generally, one could look at roads constituting a set of contiguous links who intersect at between, for instance 135 and 225 degrees (180 degrees + or - 45 degrees). Where multiple links intersect in that range, the links intersecting closest to 180 degrees can be selected to define the main road, and the others define branches.

tional Bank in 1962; nevertheless the flourishing period does not begin until the opening of the IDS center in 1973; in 1985 there are 42 skyway segments in total (Byers, 1988). The system gradually becomes mature after 1990 and stops growing in 2002. The detailed history of the development of Minneapolis skyway system can be found in Byers (1988).

The evolutionary pattern of Minneapolis Skyway System is shown in Fig. 2, where nodes represent blocks and links indicate skyway segments. The size of an octagon symbolizes the office space (or parking space if it is a parking lot) of a block. As illustrated, the blocks with larger office spaces are more likely be connected. In addition, in pace with the economic development over the course of period from 1965 to 2002, the office spaces of the block rise. The average office space per block in this area is 127,050 square feet in 1965, whereas in 2002 it increases to approximately 410,010 square feet. Fig. 3 sketches the rising of the total office space size of the blocks in downtown areawide and that of the blocks connected by the skyway system. Both curves display a similar S-curve shape, with clear-cut stages of birth (1962-1980), burgeoning growth (1980-1992), and maturing (1992-now). Trend of the development of office space sizes largely coincides with the evolutionary path of the skyway system. The space of a block can be translated into the potential employment; therefore, it can be used as an indicator for the economic importance of the block.

A summary of the measures of the network is shown in Table 1. The *roadness* of the network equals 747 meters, with 26 identified "roads" and total length of 9,713 meters. Fig. 4 shows the evolution average degree, closeness, betweenness, and eigenvector centrality measures for the skyway network from 1962 to 2005; the measures are normalized from 0 to 100. As can be seen, these indices generally decrease over time, suggesting the transformation of the network topology from tree-like and star-like structure to a homogenous grid-like one. In 1962 there was only one segment in the network, making the connected blocks all important. As few more links were added to the network, certain blocks have higher degrees of freedom than others. Tree-like structure evolved into star-like, and further a combination of tree and star structure; the average centrality indices decrease over time as the degrees of freedom of the blocks become very close. After year 1980, the indices continue to tip down and gradually levels off; at this stage the grid-like skyway network structure comes to the fore. The degrees of freedom of most blocks are the same or very close, rendering them homogeneous.

5 The Model

5.1 Assumptions

In this research, a link (skyway segment) is defined as a physical connection between two adjacent blocks.There is a building in each block, which is owned by different business owners. The value of a block is determined by its accessibility to other blocks (buildings). Building owners build links to increase the accessibility of their own buildings (and thus increase business opportunities). Skyway construction is presumably irreversible, meaning that once a link is built, it cannot be severed. Multiple iterations are run until a stable skyway network pattern emerges (i.e., no new links are built).

The street structure of downtown Minneapolis follows a grid-like planning system; the skyway links are laid out in the same fashion. Building owners are self-interested and do not have the capacity for strategic gaming (i.e. waiting for someone else to build a link for him).

5.2 Micro-economic principle of road construction

The variables used in this paper are listed in Table 2. The value of accessibility for building (block) owner i to build link k in iteration (year) t equals:

$$A_i(k,t) = \sum_{j=1}^{J} w \cdot \beta_{j,t} d_{ij,t}^{-\delta} \tag{5}$$

where w is the value of accessing one employee and $\beta_{j,t}$ is the total number of employees in block j in iteration i. It is estimated by dividing the size of office space in block j by the average space per employee (394 square feet) (consist with that in Corbett et al. (2009)). The larger the block size, the more potential employees work in the block. Thus the more valuable it is to be accessed. d_{ij} is the length of the shortest path between block i and block j. β represents the distance decay parameter. The measure of accessibility, a gravity model, is based on Levinson et al. (1994), indicating that the value of connecting to block i deteriorates geometrically with the distance.

The marginal profit for block i to build segment k in iteration t ($\Delta p_i(k,t)$) equals the extra value in iteration t compared with value earned in iteration $t-1$ minus the construction cost of link l. .

$$\Delta p_i(k,t) = A_i(k,t) - A_i(k,t-1) - c \cdot l_k \tag{6}$$

Table 1: Basic statistics of Minneapolis Skyway System in the mature stage

Variable	Value
Num of segments	73
Total length (meters)	9713.23
Number of blocks	69
Average degree centrality	3.74
Average closeness centrality	14.05
Average betweenness centrality	10.71
Average eigenvector centrality	10.28
Roadness (meter)	373.58

Among all possible links to be built, block owner i chooses the one candidate connecting block i which provides the highest marginal profit. A link will be built by block owner i only when $\Delta P_i(k,t) > 0$, otherwise no link will be constructed in this iteration. This is thus a locally selfish, myopic optimization, maximizing short term benefit for the agent itself, similar to the greedy algorithm. A network topology reaches equilibrium when no links are built for all block owners.

5.3 Simulation and verification

In the simulation, one of the key steps is to decide the values for c, w, and δ. Since the data for these variables are not immediately available, we use the trial-and-error method to run the model, and then compare the generated network with the actual network. The parameters values that produce the skyway network most similar to the actual one are documented. Given the rules described above, 40 iterations are run, each representing a year (from 1962 to 2002). In the first 40 iterations, the actual office space of a block is updated according to the block-specfic office space information from 1962 to 2002 (each iteration stands for a year). After the 40th iteration, we assume the block-specific office space does not change.

To quantify the similarity between the simulated network and the actual network is reproduced, a network matching index is proposed. Indicated by ρ, it equals:

$$\rho = \frac{\beta}{M} - (1 - \frac{\beta}{T}) \tag{7}$$

Where β is the number of simulated skyway segments matching those of the actual network. M refers to the total number of simulated skyway networks. T indicates the total number of actual skyway segments. The higher ρ is, the more similar the generated network is to the actual skyway system.

In addition, Corbett et al. (2009) that many segments in the network cannot be built because

Table 2: Description of parameters

Variables	Descriptions
$A_i(k,t)$	value of accessing block k for block i in iteration t
$\beta_{j,t}$	number of potential employees in building j in iteration t
$b_{j,t}$	office space of block j in iteration t (sq ft)
w	value of an employee in terms of accessibility
$delta$	distance decay parameter
c	construction cost per meter of segment ($)
d_{ij}	shortest distance in skyway network between block i and j
$\Delta p_i(k,t)$	marginal profit for block i to build segment k
l_k	length of segment k

of feasible considerations and political barriers; therefore, such links are seen to have no potential to be built in our simulation model. The ideal fully-connected skyway network and the segments that cannot be built are shown in Fig. 5, which provides the topological framework for simulation.

6 Results and analysis

Our simulate results reveal that the highest ρ of the produced network equals 0.65, where $\delta = 0.1$, $w = 0.6$, and $c = 70$. While it is not guaranteed that they provide the global optimal solution, they are found to be the local optimal according to the sensitivity tests. The simulation is run for 100 iterations; the network topology becomes stable after Iteration 43. The generated network in equilibrium is shown in Fig. 6. There are 105 links in the network, as opposed to 73 links in the actual network. While the simulated network consists of more links than the actual network, all segments in the actual network are predicted. As can be seen, the area near the IDC center (the center of downtown) is fully connected; most blocks have multiple routes to access other blocks. Simulated network has more segments and connects to more blocks than the actual one, and thus provides better accessibility for pedestrians from one block to another. For pedestrians starting from certain blocks, the travel time saving can be substantial. For example, from Block 50 to Block 51, pedestrians need to walk minimum five skyway segment in the actual skyway system; in the simulated network, however, the two blocks are just one segment away. In addition, it is interesting to observe triangle-like connected patterns at the bottom of the network.

The centrality measures for the simulated network are shown in Fig. 7. The centrality values for the simulated network in equilibrium are similar to those of the actual network; their evolutionary path, however, are somewhat different. Its general trend is much flatter than the actual network (see, Fig. 4). This is because they are more segments generated in the first few iterations than the growth of the actual network in the first few years. Meanwhile, the simulated network in its first twenty stages is more fragmented (the centrality measures are the average values for the small disconnected networks). Fig. 8 further compares the number of segments generated in each iteration with the actual skyway segments by year. Both curves show the S-shape. In addition, there are more links in each iteration in the simulated network than the actual network.

Fig. 9 shows the dynamic change of the continuity of the skyway network over time. There are certain spikes for the value of *roadness* as skyway segment emerge on blocks on the periphery of the network. As the network approaches equilibrium, the grid-like structure emerges, providing easy access (no or fewer left turns or right turns for pedestrians) from an origin to a destination.

The generated skyway network is somewhat different from the actual network probably due to the following reasons: (1) Besides the space of a block, other factors such as idiosyncratic, political, or block-specific economic factors could impact whether a building owner wants to construct a skyway network. (2) Profit maximization is assumed to be a building owner's only goal and each agent is always rational, which may not be the case in reality. (3) Parking garage is not separated from the office buildings in terms of measuring accessibility. (4) The sequence of the agents' decision-making is random for each round, where each agent can build one segment to the maximum. This maybe the strongest assumption in the model; however, it is difficult to obtain the information about the de facto sequence of decision making and factors considered by the owners. That said, this model can still replicate the general pattern of the final skyway network.

To further examine the network topology changes, sensitivity tests are performed for each parameter and the sequence of decision making. When changing the value of one parameter, other parameters are set to be fixed. Our hypotheses are that the greater w, the more connected the network is, and that the greater δ or c, the less connected the network is. The results of sensitivity tests confirm such hypotheses. Fig. 10 and Fig. 11 compare the generated network topology in equilibrium given different values of δ and c. As can be seen, when the value of accessibility is lower (larger δ), the network mostly consists of segments connecting blocks of large size (important nodes) in the center of downtown, the structure being more tree-like. As the value of accessibility increases, the periphery of the network expands; more blocks are included in the network where redundant paths emerge from one block to another. In addition, when the construction cost is high, only certain important nodes are connected. As the construction cost decreases, the network tends to be more connected.

7 Discussion and Conclusions

The Minneapolis Skyway System, the longest skyway network in North America, displays interesting pattern and order over its course of development. In this paper, an agent model is developed to model the growth of Minneapolis Skyway System. The model is based on the assumption that self-interested building owners build skyway segments to increase the accessibility of each's block and thereby to enhance its economic performance. Based on the gravity model, we assume the accessibility of a block is a function of the space of a block (implying the number of employees) and the trip distance from one block to another. The network topologies are evaluated by the matching ratio and the centrality measures (degree centrality, closeness centrality, and betweenness centrality). We find that our model can produce a network very close to the actual network. It seems that block size is a good indicator of the value of a block in terms of accessibility. agent-based localized rules can reflect the inherent mechanism of growth of the skyway network. Our sensitivity tests further reveals that when the economic or social conditions of places reach certain thresholds, network patterns can go through significant phase changes.

We therefore argue that the skyway network has the property of self-organization and evolution. Even without a central authority or following an optimal design, interesting network patterns emerge out of individual building owners' profit-maximizing behavior. When certain economic conditions are met, segments are first built to connect important blocks (in terms of size), and then gradually cover the blocks on the periphery. When the general economic values of blocks are low, the tree-like (non-redundant) structure centering on important nodes is the emergent topological characteristic. When the value increases, the network not only reaches other blocks farther from the center, but also provides multiple paths for already-connected blocks. Meanwhile the value of the whole network for each block increases.

Overall, this research proposes a mechanism for constructing Minneapolis skyway system. While fully recognizing that central authorities have played an important role in advancing most transportation networks, we study the dynamics of roads out of decentralized individuals' spontaneous behavior. Such a model has the potential of providing insight for the policy-makings regarding involving private endeavors in investing in public infrastructure.

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Appendix: algorithm to identify roads

Variables use in the algorithm:

- $\mathcal{L}$: list of segments with their starting block and ending block.
- J: total number of blocks.

- Ω: matrix of the connectivity of links to each other. For example, if Ω equals [[0, 1, 0], [1, 0, 0], [0, 0, 0]], it indicates that link [0] is connected to link [1] and that link [2] is not connected to either of links.
- z: a row in Ω.
- $\theta(i, j)$: the acute angle between the two contiguous links, link i and link j. If the acute angle between two contiguous links equals 180 degrees, then the two links are seen as part of one road.
- k, m: indexes of links.
- $index$: number of connections that one link has to other links.
- Ψ: list of links (indexed by id) belonging to the same road. For instance, Ψ = [2,0] means that a road consists of link[2] and link[0].
- Π: road set. For example, if Π = [[0, 3] [1, 2]], it means link [0] and link [3] belong to the same road, whereas link [1] and link [2] constitute another road.

Algorithm to find roads.

Algorithm 7.1: FindingRoads($\mathcal{L}, J$)

comment: initialize a full zero link matrix

$\Omega \leftarrow []$
for $i \leftarrow 0$ **to** J
  do $\begin{cases} z \leftarrow [] \\ \textbf{for } j \leftarrow 0 \textbf{ to } J \\ \quad \textbf{do } z \leftarrow z + 0 \\ \Omega \leftarrow \Omega + z \end{cases}$

comment: find two links that can be seen one road; update the link matrix.

for each $i, j \in \mathcal{L}$
if $\theta(i, j) = \pi$
  then $\Omega_{i,j} \leftarrow 1$

comment: Find roads based on the link matrix

$k \leftarrow 0$
$index \leftarrow 0$
for $i \leftarrow 0$ **to** J
  do
    for $j \leftarrow 0$ **to** J
      do $index \leftarrow 0$
    Π**if** $\Omega_{i,j} = 1$
      then $index \leftarrow index + 1$
    if $index = 1$
      then
        $index \leftarrow 0$
        $k \leftarrow j$
        $\Psi \leftarrow []$
        for $m \leftarrow 0$ **to** S
          do if $\Omega_{k,m} = 1$
          then $index \leftarrow index + 1$
        if $index = 2$
          then $\begin{cases} \textbf{if } \Omega_{k,m} = 1 \textbf{ and } m \notin \Psi \\ \quad \textbf{then } \Psi \leftarrow \Psi + m \end{cases}$

    comment: add road Ψ to road set Π

    $\Pi = \Pi + \Psi$

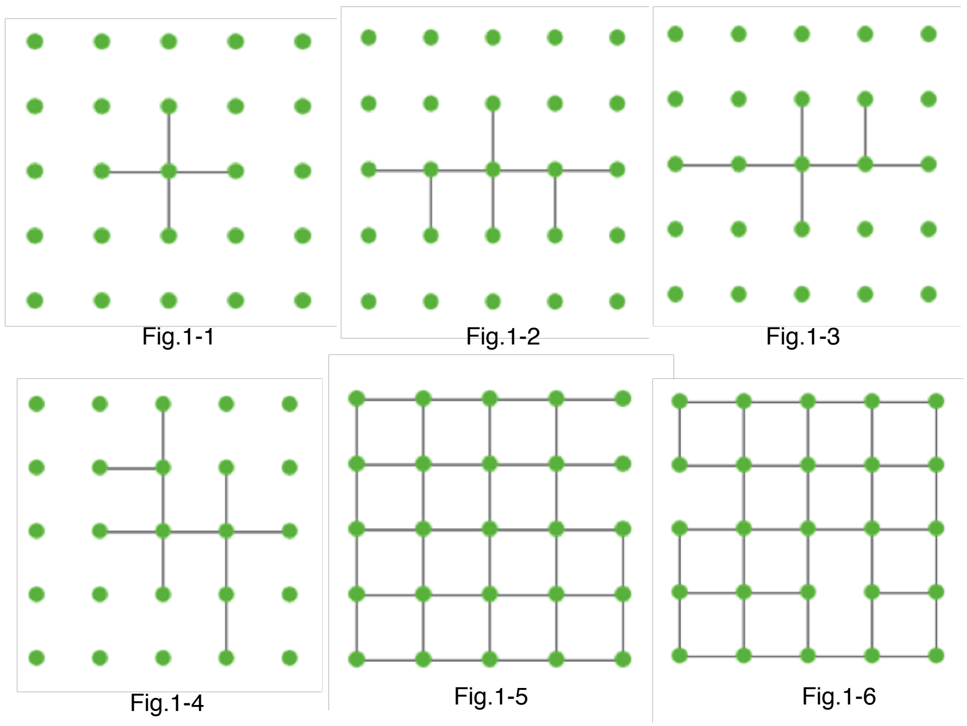

Figure 1: Examples to illustrate the concept of roadness. In Fig.1-1, there are two roads; each has two links. The roadness equals 2. Fig.1-2 has four roads; the longest one has four links. The roadness of the graph equals 2. There are three roads with total seven links in Fig.1-3; the roadness equals 2.33. In Fig.1-4, the graph owes four roads and ten links; the roadness is 2.5. In Fig.1-5, there are ten roads with 30 links in total, thus the roadness equals 3. Fig.1-6 has 12 roads; the roadness equals 2.5.

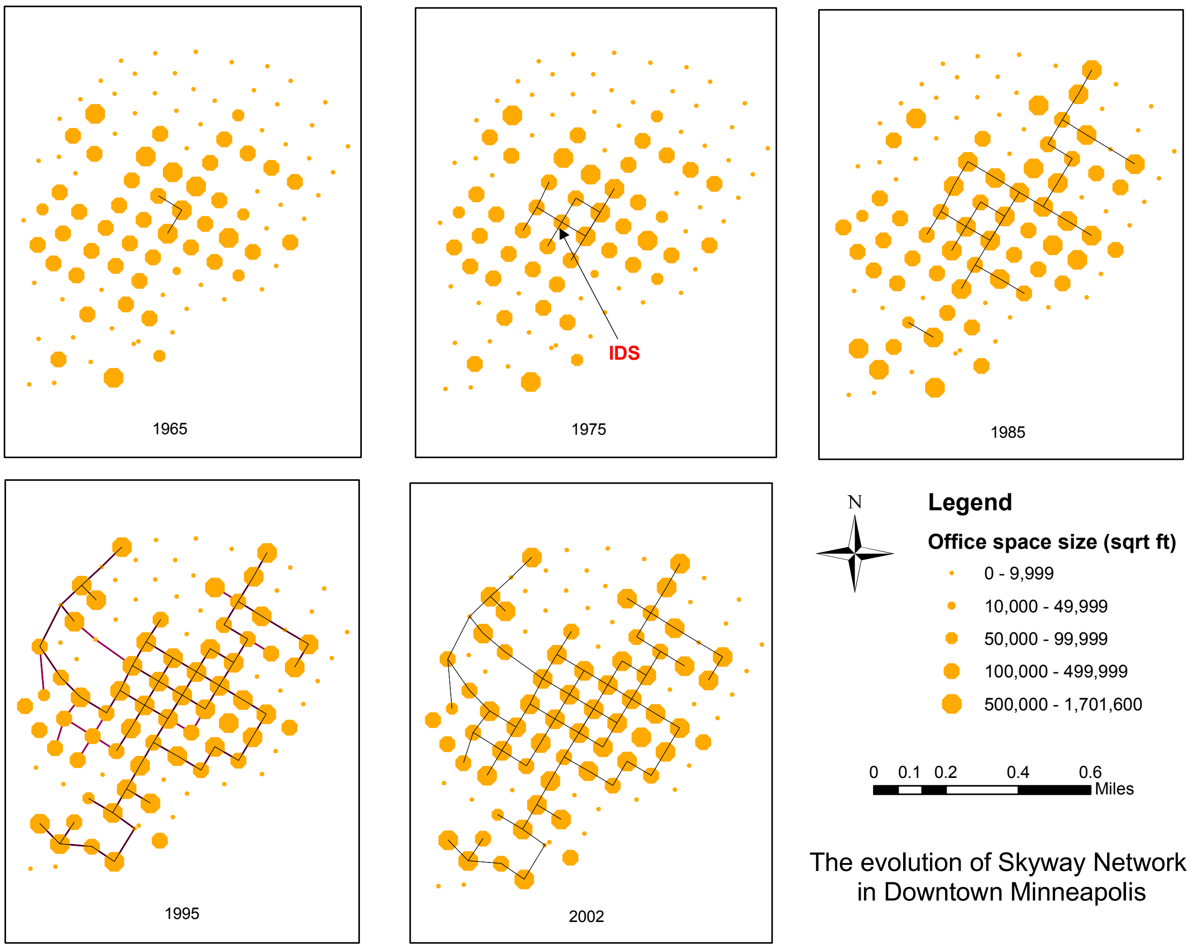

Figure 2: The evolution of Minneapolis Skyway System from 1965 to 2002. Links represent skyway segments. Octagons of different sizes symbolize blocks of different office (parking) spaces, implying the importance of the blocks.

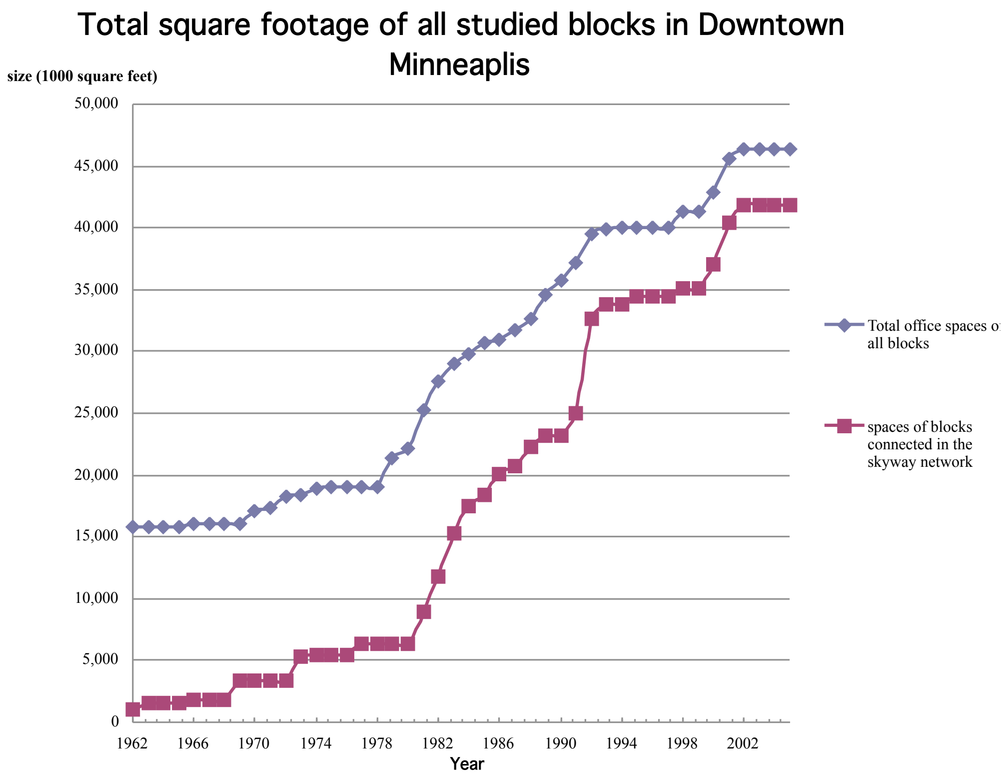

Figure 3: The evolution of total office space size in downtown area and the total office space of the blocks connected by the skyway system over time.

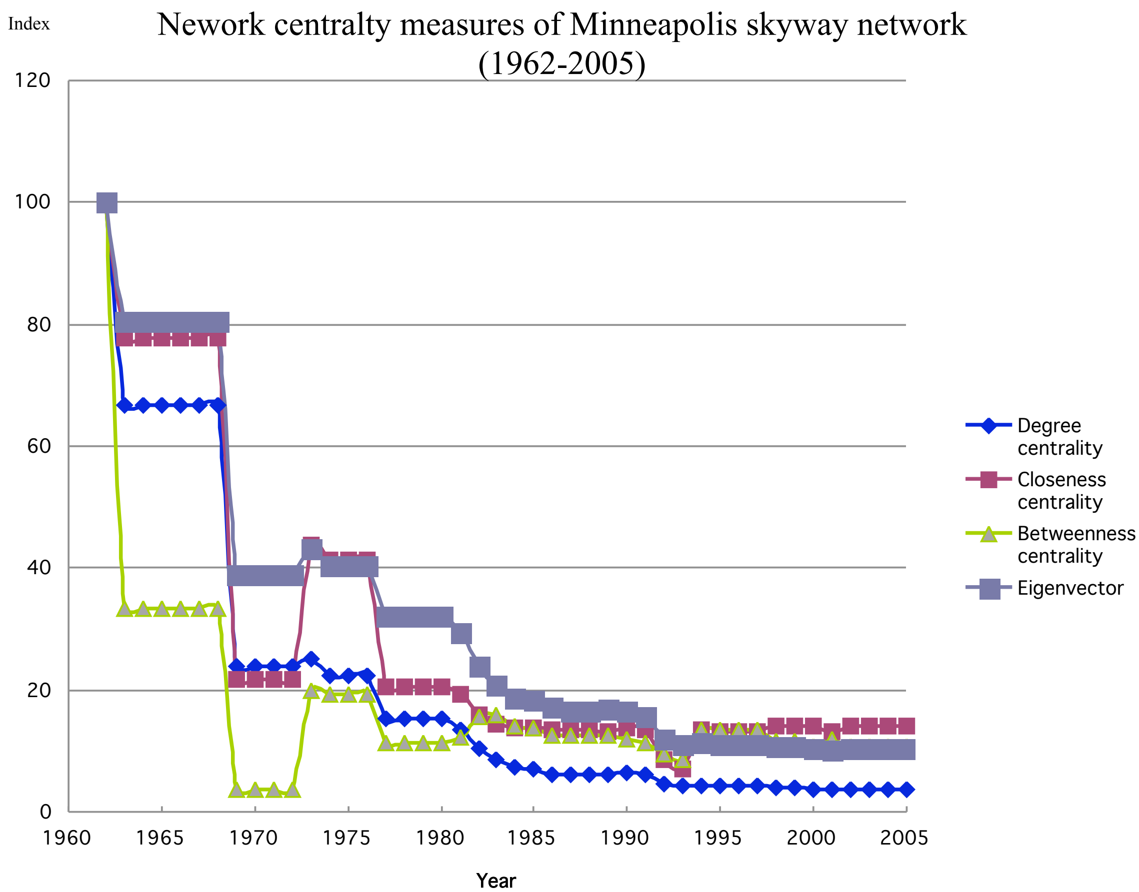

Figure 4: The centrality measures of Minneapolis Skyway Network from 1962 to 2005.

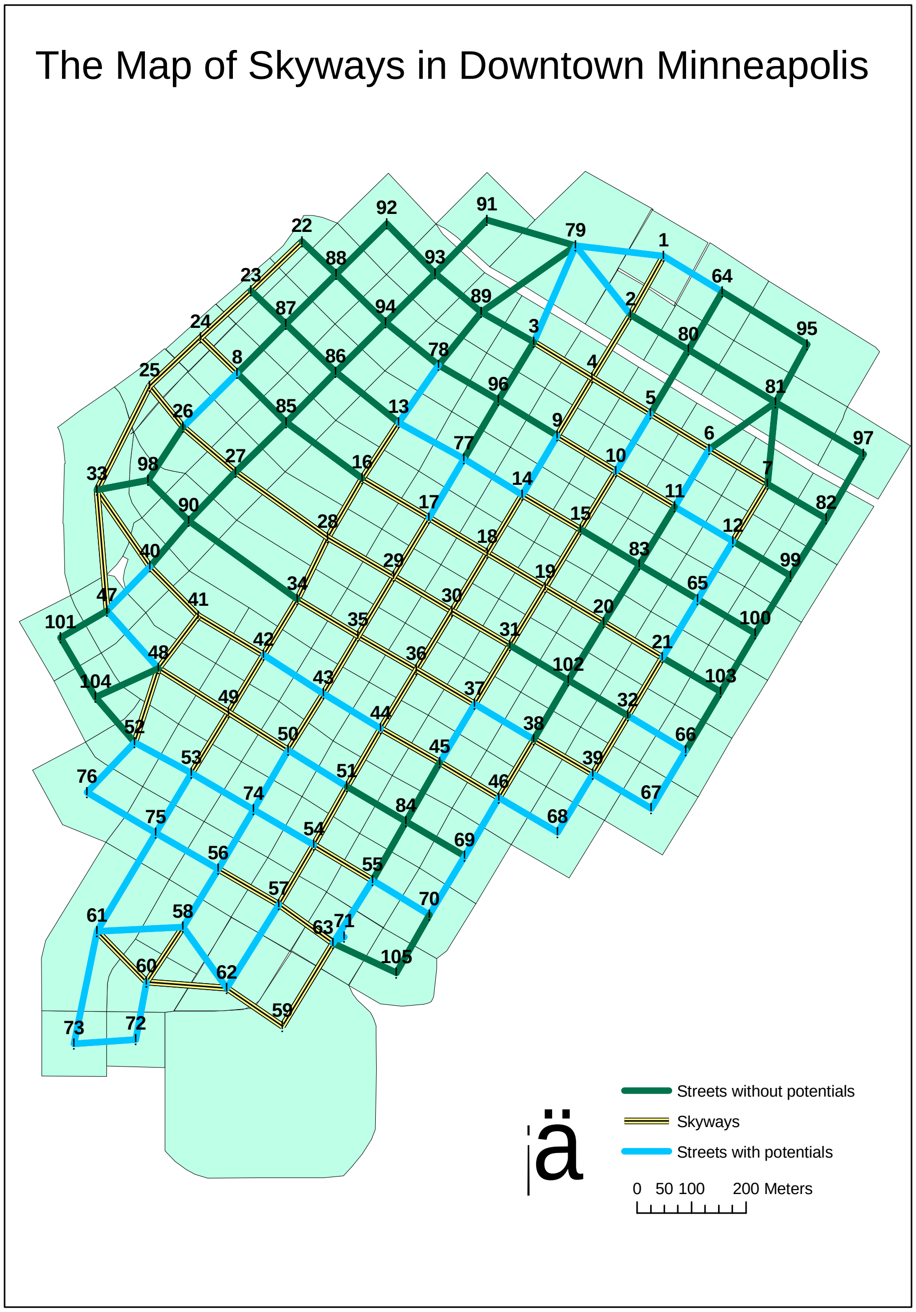

Figure 5: Fully connected network and the segments that have the potential or cannot be built (Source: Corbett et al. (2009)).

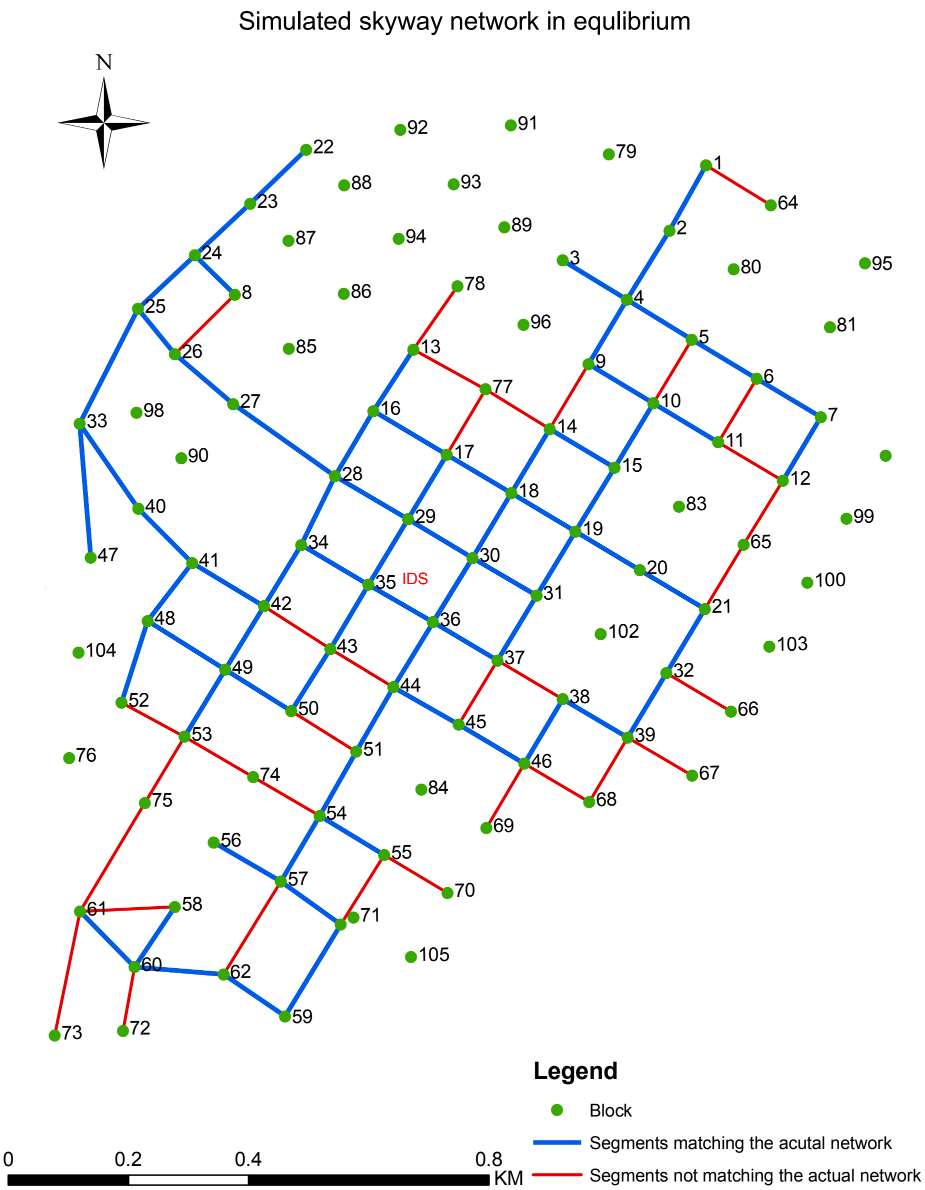

Figure 6: Simulated skyway network in equilibrium (after Iteration 43), as a comparison to the actual skyway network after year 2002.

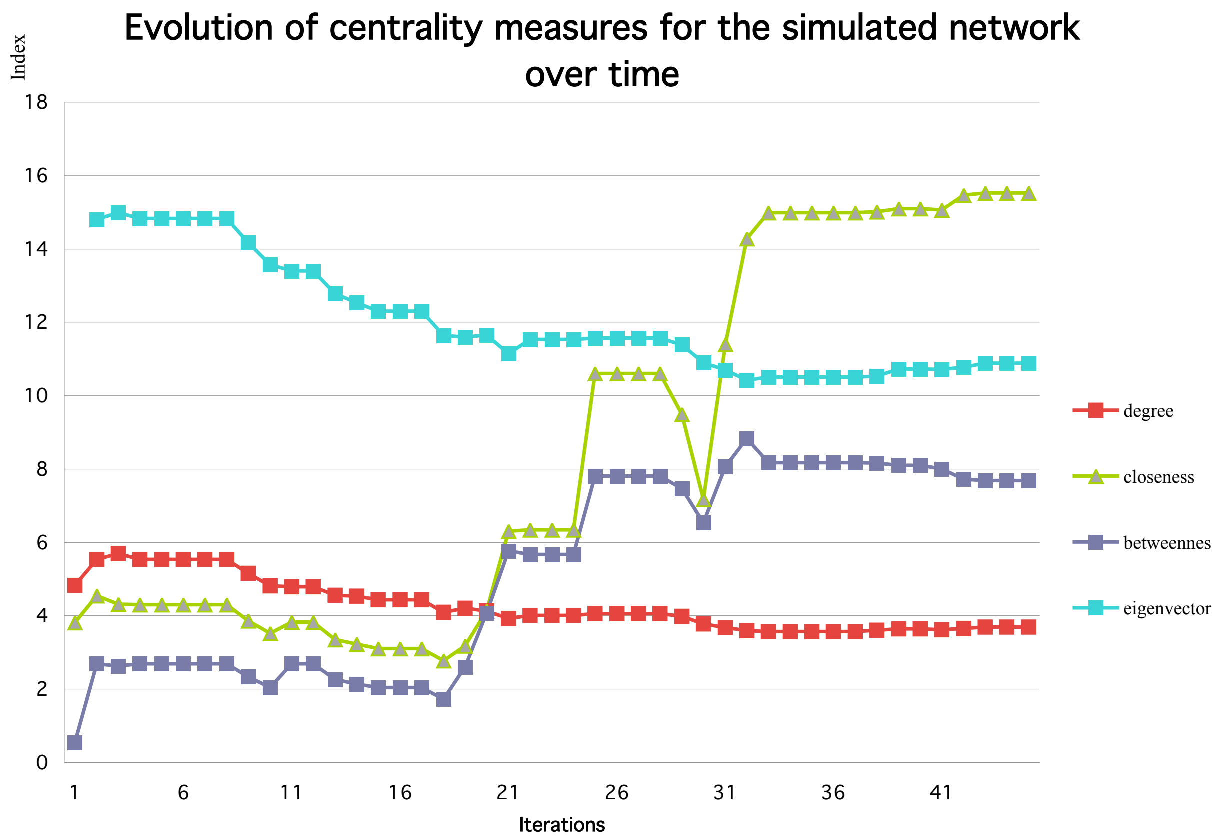

Figure 7: The centrality measures of the simulated network from Iteration to Iteration 44.

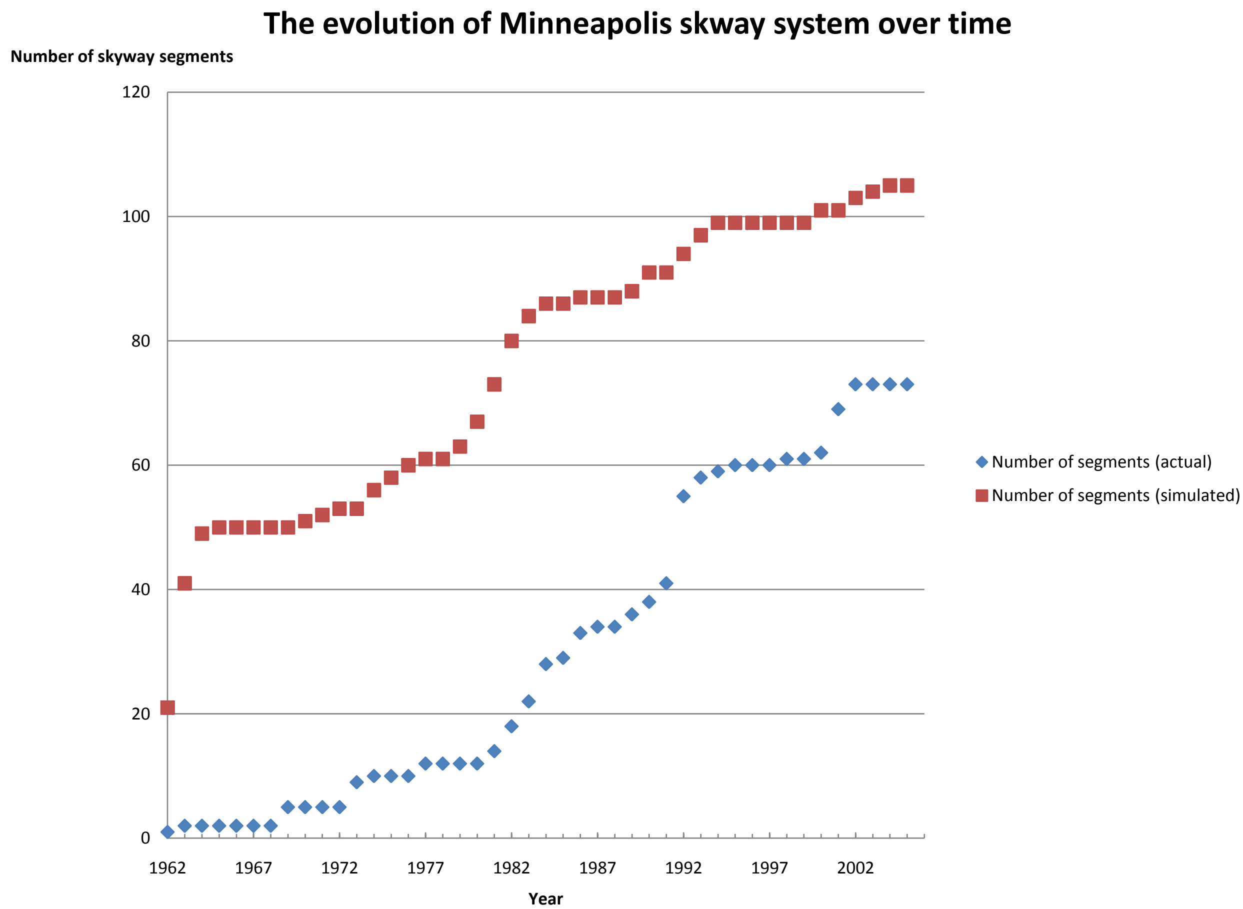

Figure 8: Cumulative number of of segments over time.

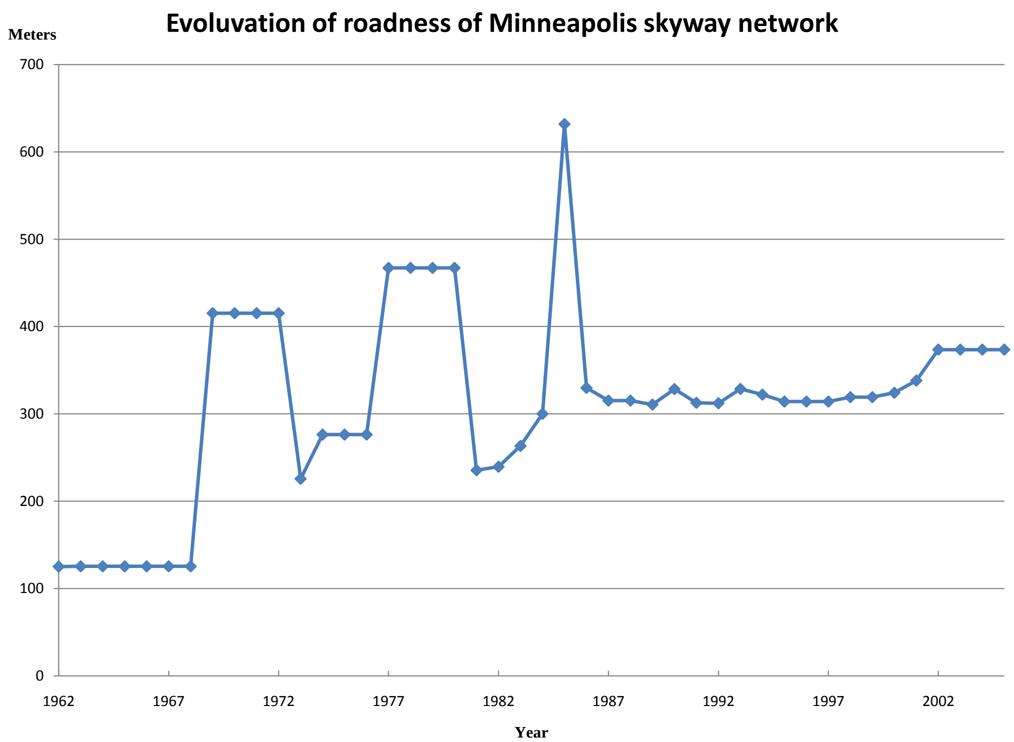

Figure 9: The evolution of the continuity measure, *roadness*, over time.

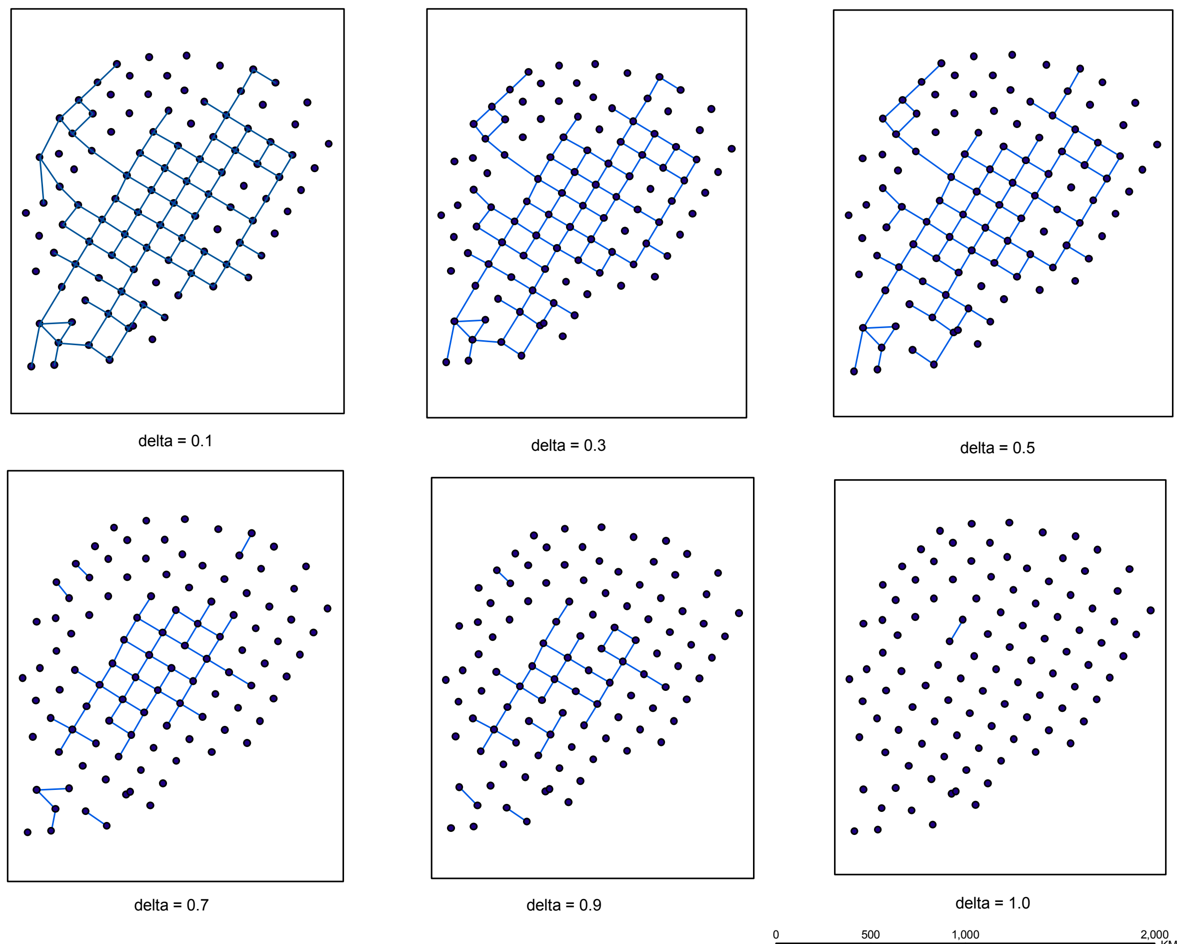

Figure 10: Sensitivity tests on δ. Network topology changes as the accessibility of the blocks changes.

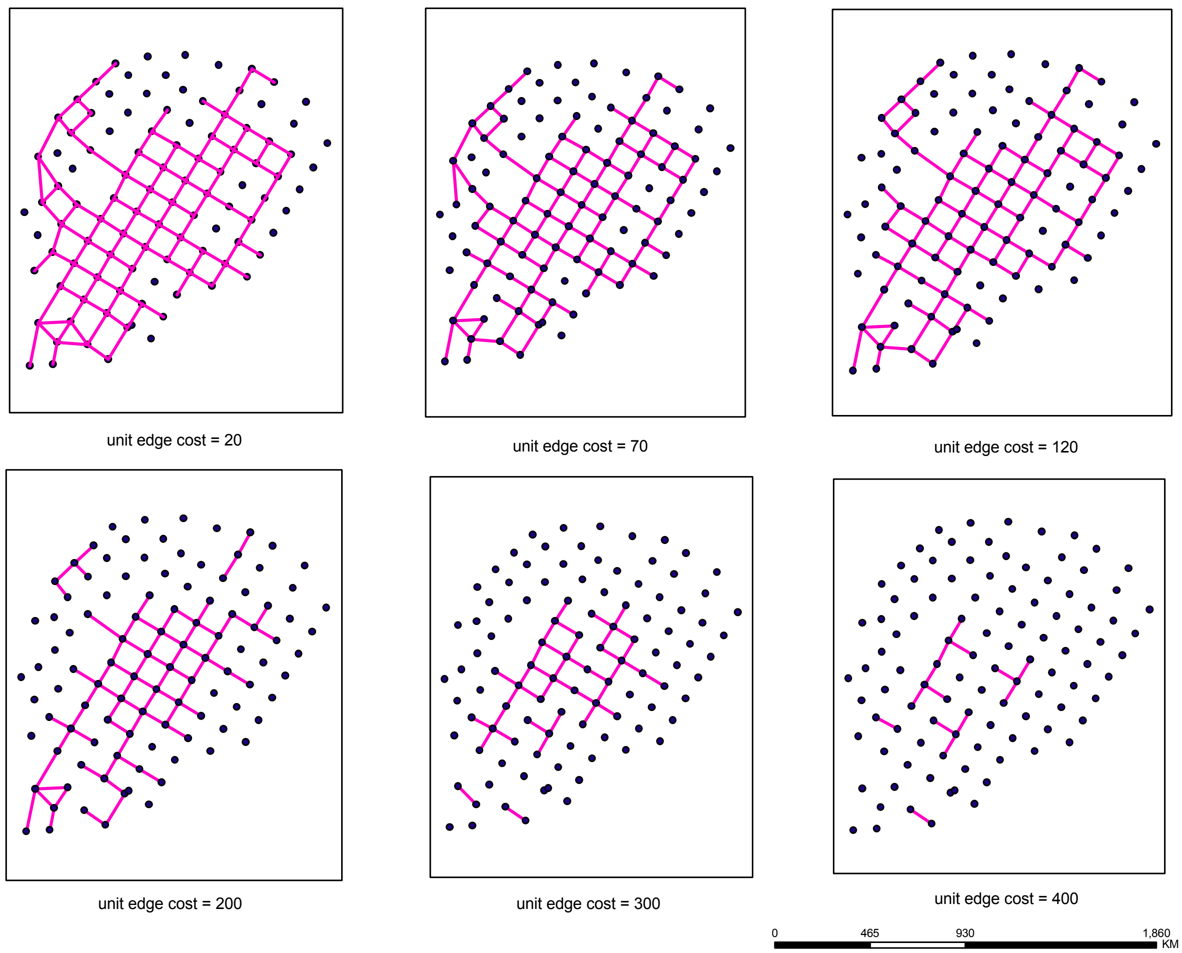

Figure 11: Sensitivity tests on c, unit edge cost per meter. Network topology changes as the unit construct cost of skyway segments changes.